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Latest news and knowledge updates

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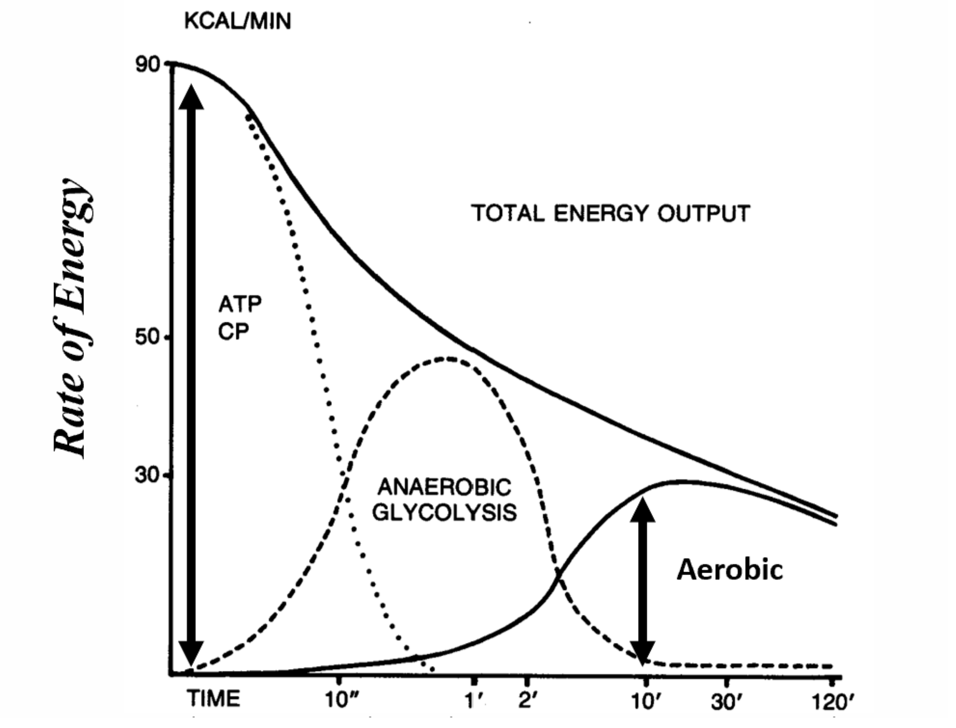
Energy Systems

Not just for the endurance crowd.

The energy systems of the body that provide the energy during physical activity can be and are often misunderstood. This happens because of the idea that only those in endurance sports need to be concerned with them, or how they have been taught to many of us as sports scientists and/ or coaches. When I was a young coach, I could recite all the systems, their bio pathways because I was able to memorize the chapter in the text by McArdle Katch and Katch. But what I failed to understand was how important their interactions with all the other systems or "chapters" in the book.



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The Three Energy Systems

All ATP (energy) is regenerated from one of 3 biochemical pathways, also referred to as energy systems: The Phosphocreatine System, The Anaerobic Glycolytic System, and the Aerobic System. Each system replenishes ATP at different rates, and each system has a different capacity for the amount of ATP that it can regenerate. The faster an energy system can regenerate ATP, the less total ATP it can replace. Because of this, the body is able to replenish ATP despite large fluctuations in exercise intensity and duration.

The sequence and relationship of the three energy systems in greater detail can be seen in the graphic here. We can see the rate of energy output in kcal / min, and along the bottom is time of exercise, As we can see the unit along this bottom change from seconds (closer to the beginning) to minutes further down the axis. The solid black line along the top of the chart depicts the total rate or amount of energy output of a maximal intensity effort.

We can clearly see the ATP-CP system has the highest maximal amount of energy production, whereas the Aerobic system has the lowest maximal amount. What is known as the short-term energy system, the ATP-CP system, provides little energy production in exercise efforts longer than 10-15seconds, whereas the aerobic system continues to produce energy for hours. Anaerobic Glycolysis provides midrange rates and timeframes of energy supply. It effectively 'buys times' for aerobic metabolism.

We can also see the overlap of energy systems; as the rate of energy production by one system is decreasing, the subsequent system is increasing. In this way, the 3 energy systems allow for a continuous energy supply across time. At no time does one energy stem turn off as one system turns on.

Howald H., vonGlutz G., and Billeter, R. (1978). Sequence and Relationship of the Energy Systems

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The individual energy systems.

The Phosphocreatine System (ATP-PC)

The phosphocreatine system is the main system for immediate regeneration of ATP. It occurs within the muscle and involves the high-energy phosphate compound called phosphocreatine, and the enzyme creatine kinase. During exercise. as the concentration of ADP in the muscle increases due to a breakdown of ATP, the high-energy bond in phosphocreatine is released by creatine kinase and uses the resulting free energy and phosphate to recreate ATP, leaving behind creatine.

This reaction does not need oxygen, and there are no significant fatigue related by-products (such as lactic acid). This energy system is sometimes called the anaerobic a-lactic system, or just the a-lactic system. This is a single-step reaction that occurs within the sarcoplasm of the muscle cell, ATP can be regenerated at a remarkably high rate. Peak rate of ATP production by this system occurs in less than 5 seconds. Although skeletal muscle can hold 4-5times more phosphocreatine than ATP, the amount of phosphocreatine that can be stored within a cell the ATP-CP system has its limits. Because the system has a low capacity for ATP production, if maximal exercise persists for longer than 10-15 seconds, another energy system will become the dominant method of ATP production. The ATP-PC system is the primary source of energy for strength, power, and sprint exercise.

The Anaerobic Glycolytic System

The Anaerobic Glycolytic system is the dominant energy system for short-term regeneration of ATP. Glycolysis occurs within the sarcoplasm of the cell and involves breaking down muscle glycogen or glucose. To keep the concept simple, there are a number of steps, 7 to be exact, to break down the glycogen or glucose, however the last reaction of this entire series is under the control of the enzyme phosphofructokinase or PFK. The activity of PFK is considered to be rate-limiting during maximal effort exercise, and it is considered a key enzyme of the pathway.

Up to this point, the reactions of what we call glycolysis have utilized ATP; the process has been consuming energy. However, in a series of 7 reactions, the system becomes positive energy producing as ADP is converted back into ATP while we are left with pyruvate, which is the main end-product of glycolysis. Another key enzyme, pyruvate kinase, controls the final reaction of the series to produce pyruvate. Under aerobic conditions (in the presence of oxygen), pyruvate remains available for conversion for further energy production via the Krebs cycle. This is known as aerobic glycolysis and is a component of the aerobic energy system.

However, without the presence of sufficient oxygen, a compound called NAD+, is not sufficiently regenerated by aerobic metabolism. NAD+ is a required in the energy-producing reactions of glycolysis and without it, the pathway would stop. Under anaerobic conditions, the enzyme lactate dehydrogenase combines pyruvate with NADH and H+ to form NAD+ and Lactic Acid, ensuring a continued supply of NAD+ for use in glycolysis. This is known as anaerobic glycolysis.

As lactic acid is produced under these conditions, this system is sometimes called the Anaerobic Lactic System, or the Lactic System. Compared to the single-step reaction of the ATP-CP system, the multi-step process of Anaerobic Glycolysis has a lower, more moderate rate of energy production. Glucose and glycogen are not as limited as phosphocreatine in terms of storage, so the capacity of the anaerobic glycolytic system is also greater than the ATP-CP system. However, the conversion of pyruvate to lactic acid is a temporary time-buying solution. Combined with the accumulation of fatigue-related by-products, such as hydrogen ions, the capacity of this system is typically a moderate 45-90 seconds, and certainly less than 120seconds. This system is the dominant energy source for longer sprint event, like 400 and 800m sprints.

The Aerobic System

The Aerobic system is the dominant energy system for long-term regeneration of ATP. It can involve the breakdown of carbohydrate, fat, or protein through a number of pathways. These reactions begin in the sarcoplasm of the cell and are completed in the mitochondria. The dominant aerobic pathways are the Krebs cycle, and Oxidative Phosphorylation via the Election Transport Chain. These are terms that will bring shivers to anyone who has taken a university course in biology. The Krebs cycle is a multi-step pathway of which its main function is the production of hydrogen ions that fuel the Electron Transport Chain and Oxidative Phosphorylation. The electron transport chain refers to a series of steps that occur the mitochondria where electrons are passed between a series of intermediaries, progressing from those with high potential energy to those with lower potential energy, similar to a series of cascading waterfalls. In doing so, ATP is regenerated, and electrons are delivered to their final destination: reducing with oxygen to form water. The process of electron transport generates a source of potential energy that further regenerates ATP.

Carbohydrates, fats, and protein must be broken down into a common substrate to enter these pathways and be metabolized aerobically. Stored carbohydrates (or glycogen) are broken down to glucose, and then to pyruvate. Pyruvate is then converted for use in the Krebs cycle. The breakdown of fat results in a glycerol molecule and three free fatty acids. A process known as beta-oxidation converts free fatty acids to acetyl-CoA for entry into the Krebs cycle, whereas glycerol can directly enter glycolysis for further processing. Depending on the type of protein, its breakdown can result in creation of pyruvate, acetyl CoA, or intermediaries used in the citric acid cycle. As oxygen plays a critical role in the regeneration of ATP, this system is sometimes called 'oxidative metabolism'. Aerobic energy production required multiple stages of fuel breakdown, and transport of intermediaries both throughout the body and within the cell. Accordingly, this system has the lowest power of the 3 energy systems. However, requiring only a supply of oxygen and macronutrients, while producing water and carbon dioxide as by-products, the capacity of the aerobic system is very large. Aerobic Metabolism is the primary energy system for any activity that exceeds several minutes in duration.

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Relative Energy Contributions

The latest updates

Table II. Estimates of anaerobic and aerobic energy contribution during selected periods of maximal exercise

Duration of exhaustive exercise (sec)	% Anaerobic	% Aerobic[a]
0-10	94	6
0-15	88	12
0-20	82	18
0-30	73	27
0-45	63	37
0-60	55	45
0-75	49	51
0-90	44	56
0-120	37	63
0-180	27	73
0-240	21	79

a Approximately ± 10% at the 95% prediction level (refer table I and fig. 2).

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Knowledge of the power and capacity of energy systems is useful when deciding which system to prioritize for athletes of different events of physical activity. A simple starting point is to ask "what is the total energy contribution of an energy system for a given duration of maximal effort?". The table shown provides estimates for the relative contribution of anaerobic and aerobic energy systems during maximal exercise of various lengths.

For example, approximately 70% of the energy used during an all-out 30-second effort comes from anaerobic sources whereas, for a 3-minute all-out effort, approximately 70% of the energy contribution is from aerobic sources. For repeated sprint efforts, in general, the aerobic contribution increases with increasing number of efforts performed, increasing length of efforts, reduced rest in between efforts and when recovery between efforts is active instead of passive.

Gastin, P.B. (2001). Energy System Interaction and Relative Contribution During Maximal Exercise. Sports Medicine. 31(10): 725-741.

McGawley, K., Bishop, D. J. (2015). Oxygen uptake during repeated-sprint exercise. Journal of Science and Medicine in Sport. 18: 214-218.

Girard, O. Mendez-Villanueva, A., Bishop, D. (2011). Repeated-Sprint Ability-Part I: Factors Contributing to Fatigue. Sports Medicine. 41(8): 673-694.

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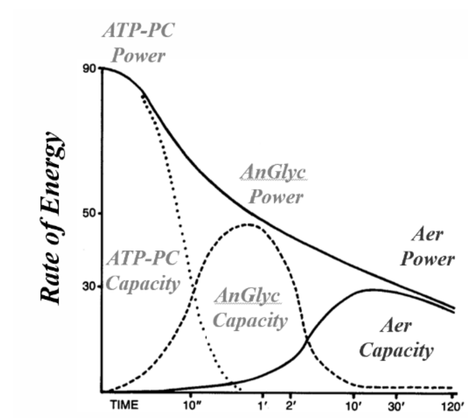
Power and Capacity of the systems

When discussing energy systems, it is typical to use the terms power and capacity. The power of an energy system refers to its maximum rate of energy production. The capacity of an energy system refers to the maximum amount of energy that can be produced by it.



Power as depicted as the thick black line and capactity of the systen as depicted as the area under to curve.

Concluding Remarks

It is difficult to take a broad topic such as the energy systems and condense into a short document. However, if referring to the relative energy contributions, it begins to highlight the need for the development of all the systems during training. Unless the event is less than 30 seconds or greater than 180 minutes, the contribution comes from both the anaerobic and aerobic. Under those two extremes, would it be logical to specialize, but very few sports fit into those two categories. To neglect one system because, "it's an anaerobic sport" is neglecting all around development for example. The aerobic system allows for the recovery between successive bouts; think shifts in hockey. The development of the anaerobic systems allows for the ability to have that "second gear" when you need to explode past an opponent.

This is further highlighted when working with developing athlete. The aerobic system is highly trainable at a young age due to the ability of the heart to adapt to training. If this window is missed at the appropriate time in the growth and maturation, the ability to make change to the "endurance" of an athlete will have to take a different approach. This is something that I personally wish I knew more when I was training myself, but also as a young coach. I can say now that my methods to take a much more rounded approach to training the energy systems.

For more information a great resource for information on the topic can be found in Science of Sport Training: How to plan and control training for peak performance by Thomas Kurz.